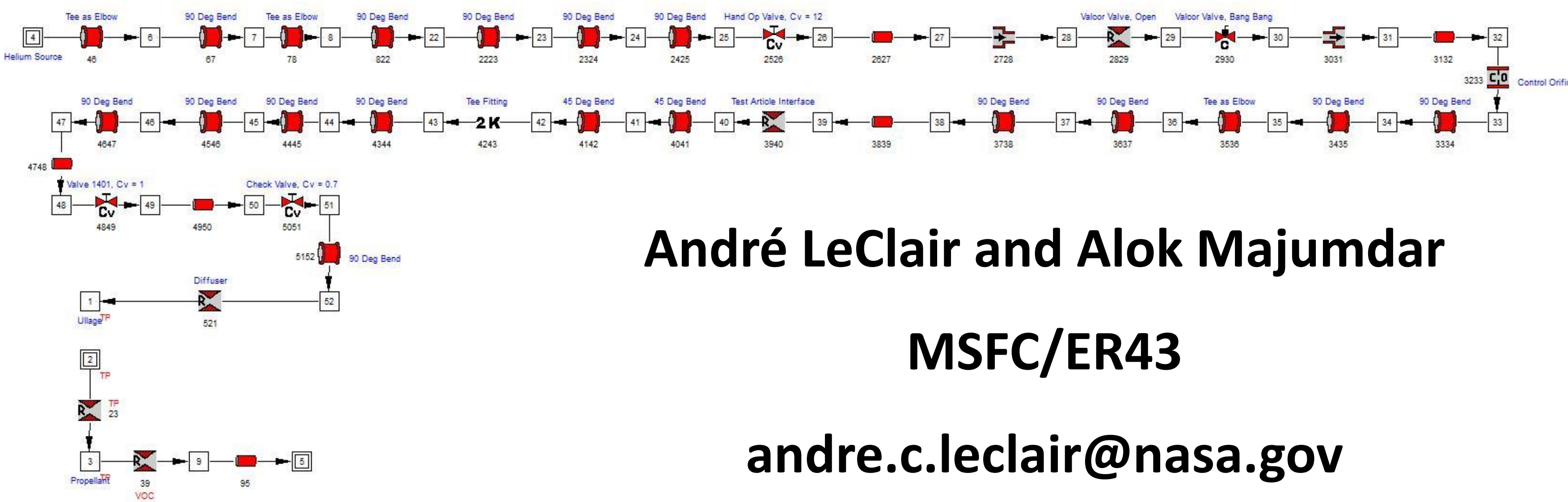
Thermo-Fluid Modeling of the Pressurization and Draining of a 1000-Gallon Cryogenic Tank with GFSSP



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TFAWS 2016

Outline

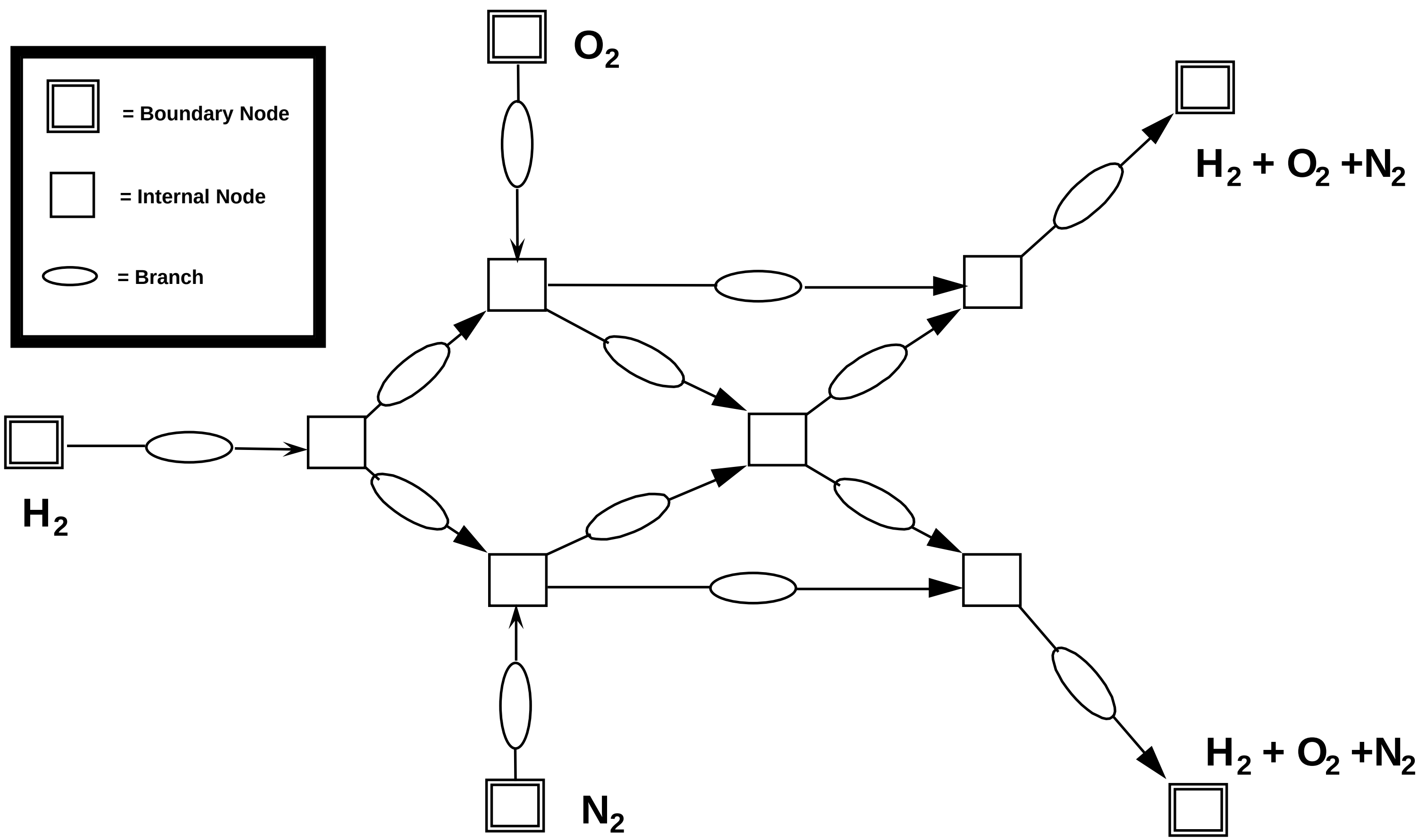
- Background on GFSSP
- Background on IVF-1000 Tank
- Model Details
- Comparison with Test Data
  - LH_2
  - LN_2
- Discussion
- Forward Work

GFSSP

- GFSSP is the Generalized Fluid System Simulation Program.
- It is a general-purpose computer program to compute pressures, temperatures, and flow rates in a flow network.
- It was primarily developed to analyze:
  - Internal Flow Analysis of a Turbopump
  - Transient Flow Analysis of a Propulsion System
- GFSSP has been in continuous development at MSFC since 1994.

GFSSP

- GFSSP discretizes a system into a flow network of **nodes** connected by **branches**.

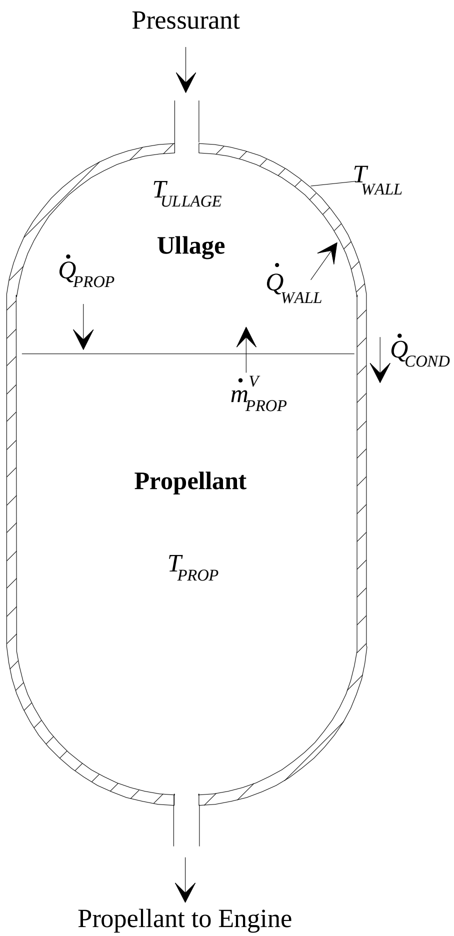


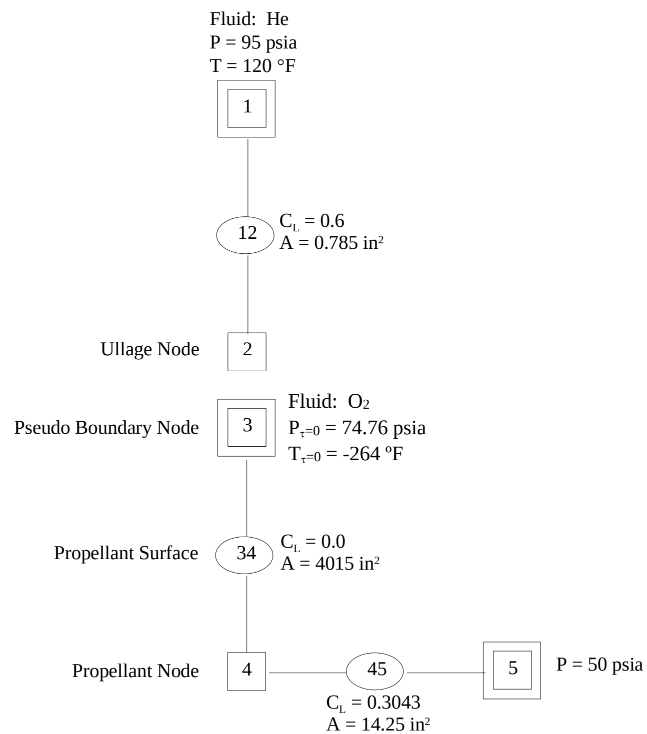
GFSSP

- Conservation of mass and energy is solved in the nodes to get pressures and temperatures.
- The momentum equation is solved in the branches to get flow rates. The branches represent empirical laws of transport processes, such as pressure drop in a pipe.
- Integrated property packages (GASP/WASP and GASPAK) provide fluid properties.
- Built-in options include
  - Pressure and flow regulators
  - Opening/closing of valves
  - Heat exchangers
  - Tank pressurization

Tank Pressurization Option

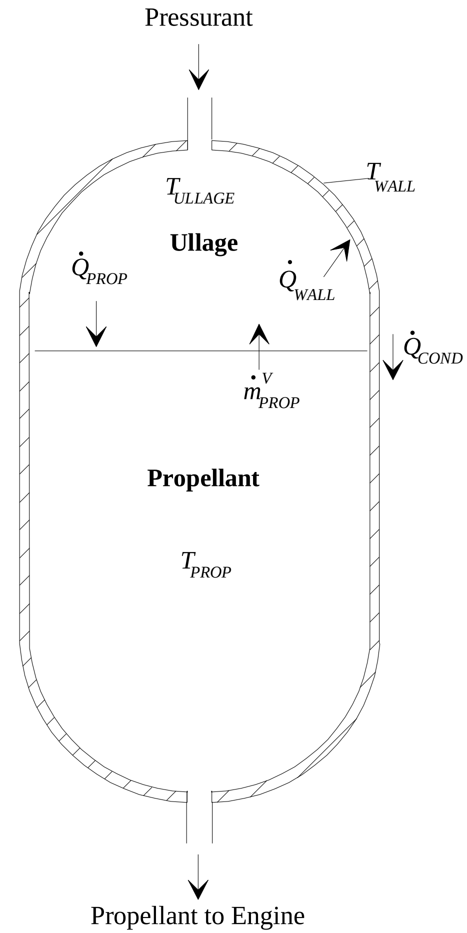
- GFSSP has a built-in tank pressurization option.
- A single ullage node is separated from a propellant node by a pseudo-boundary node.





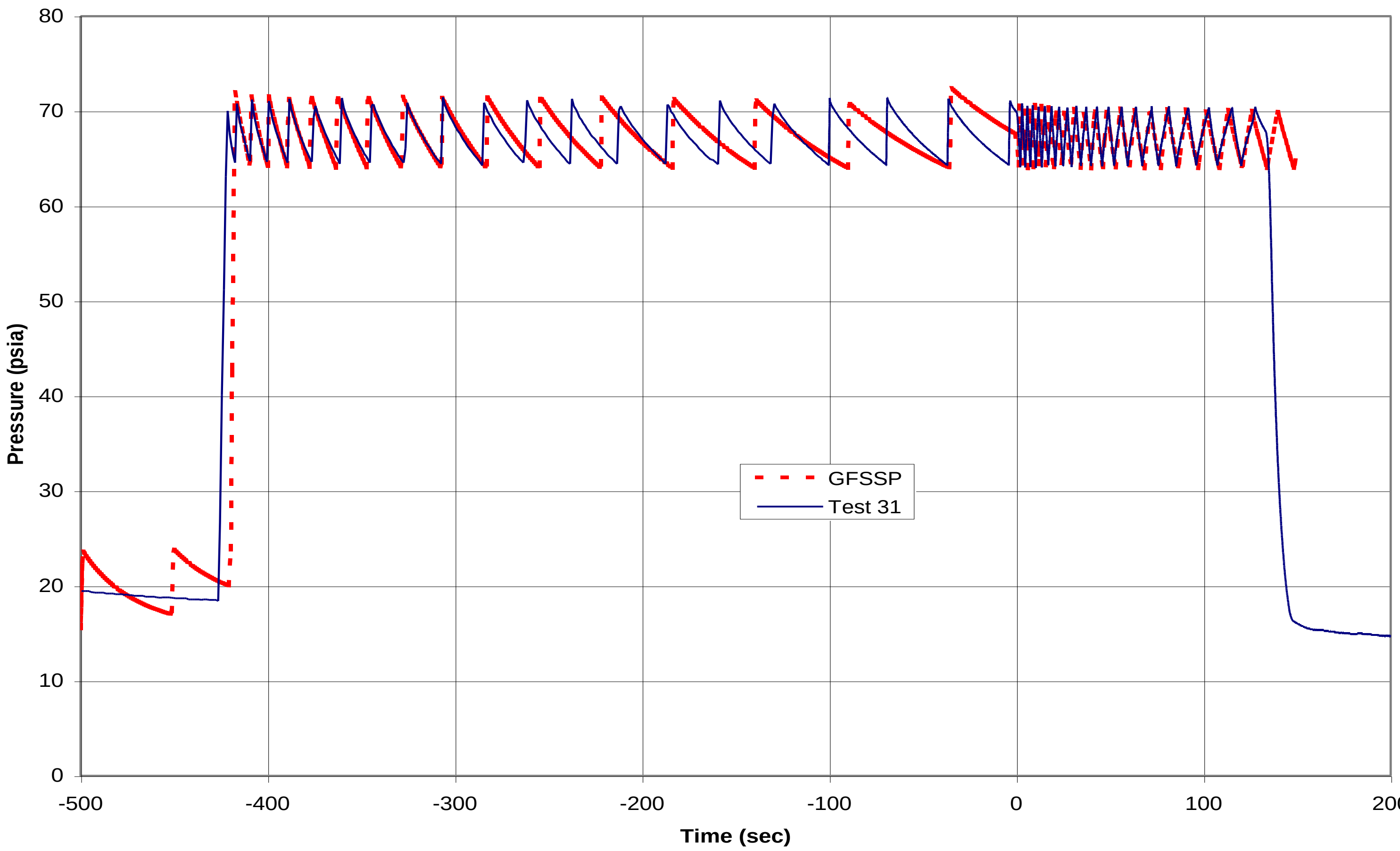
Tank Pressurization Option

- As the model runs and the tank drains, the code automatically tracks:
  - Volume of ullage and propellant nodes
  - Propellant depth and head (ρgh)
  - Ullage-to-wall heat transfer
  - Ullage-to-propellant heat transfer
  - Average temperature of uncovered tank wall
  - Pressure and temperature of ullage node
- Heat transfer calculations are based on natural convection correlations recommended by Elliot Ring (1964).
- Correction factors may be applied to the heat transfer rate.



Tank Pressurization Option

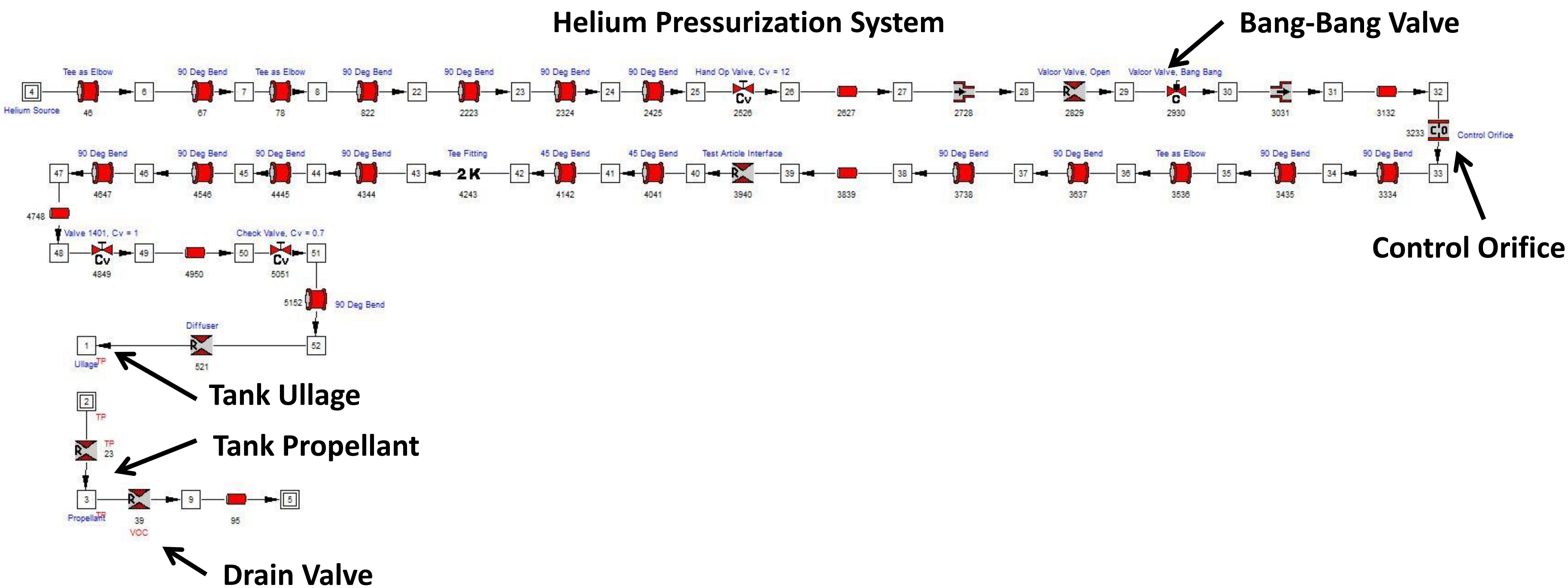
- An early application was modeling of LOx tank pressurization during FASTRAC engine testing at Stennis Space Center.



IVF 1000 Tank

- Integrated Vehicle Fluids (IVF) is a test program under NASA's eCryo project, which evolved from the Cryo Propellant Storage and Transfer (CPST) project.
- The IVF-1000 test tank was formerly known as the CPST Engineering Design Unit (EDU).
  - Dimensions: 87" x 67"
  - Volume: 144.5 ft^3 (1080 gal)
  - Mass: 400 lb of aluminum alloy
  - Insulation: 1.25" of SOFI + 60 layers MLI
- In September 2015, a series of pressurization tests were performed on the IVF-1000 tank. The tank was filled with LH_2 and LN_2.

Model Details

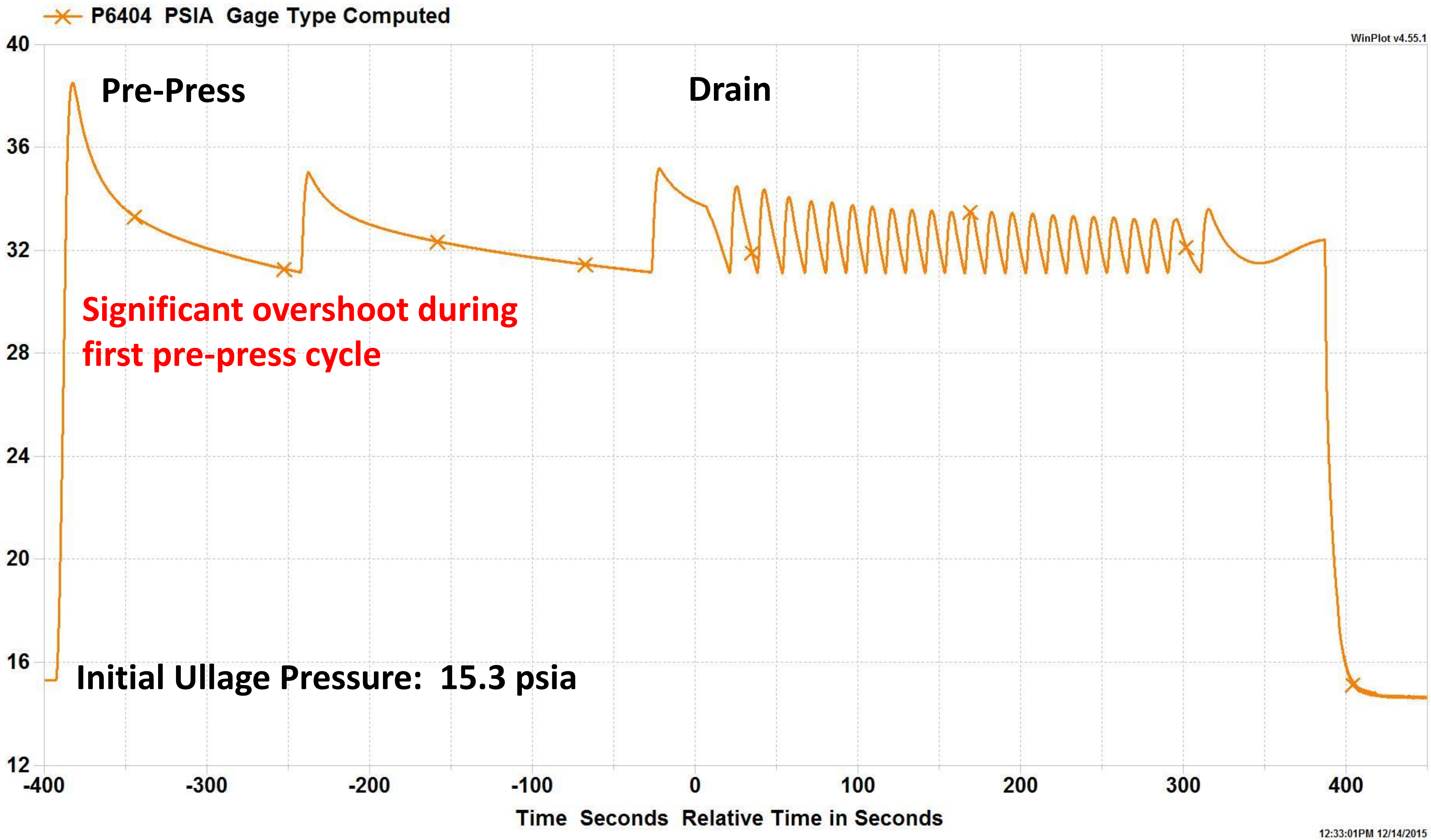


- Helium press system includes bang-bang valve and control orifice.
- Propellant drain valve is closed during pre-press. During drain, it opens to an area chosen to match the observed drain rate.

LH_2 Test Description

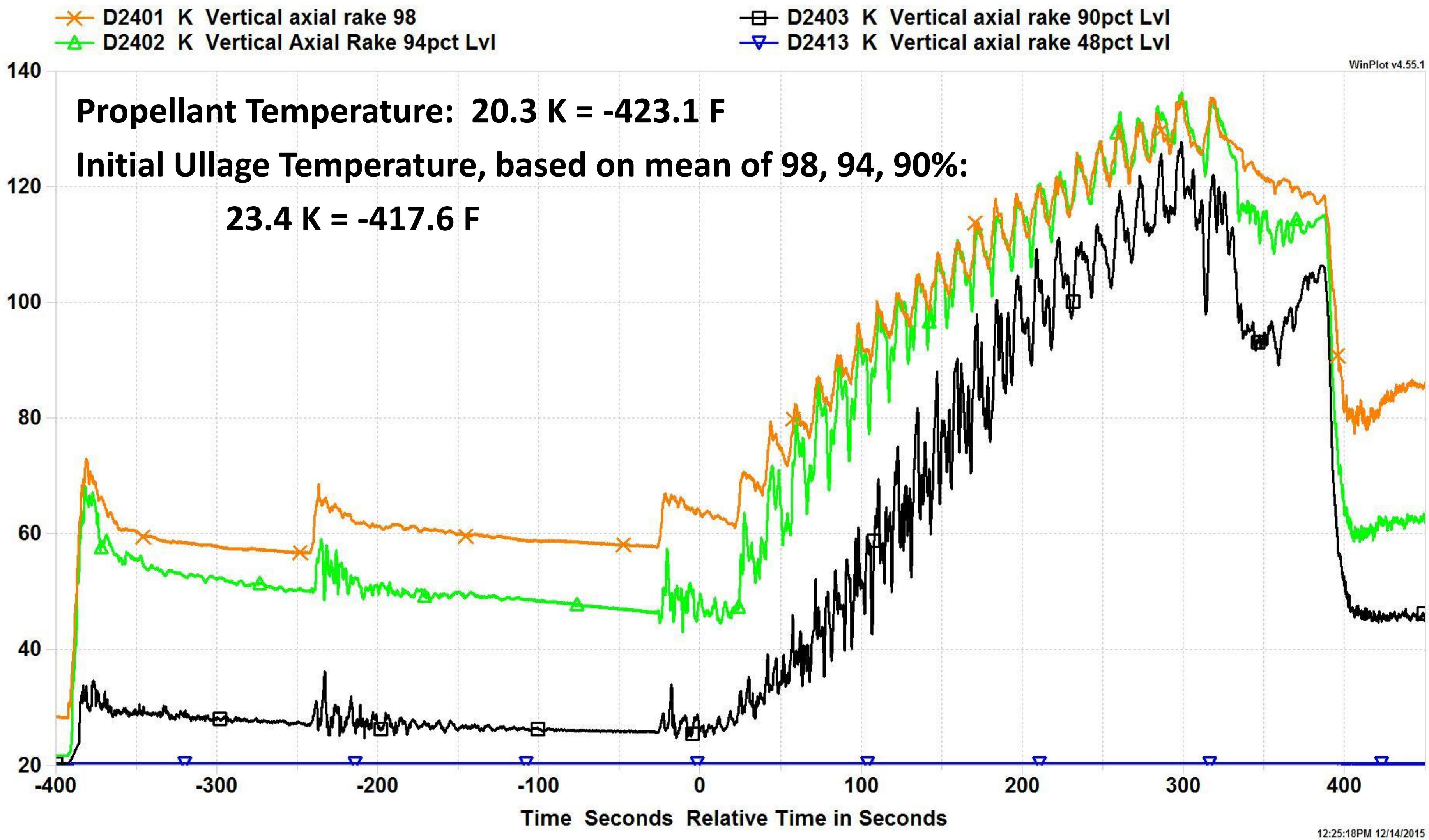
- LH2 propellant
- He pressurant
- Bang-bang valve set to maintain 31-32 psia range.
- Tank drains from 89.2% to 69.8%.
- Pre-press starts at ~T-392 sec.
- Drain starts at ~T+7 sec.
- Drain stops at ~T+295 sec.

Pressure

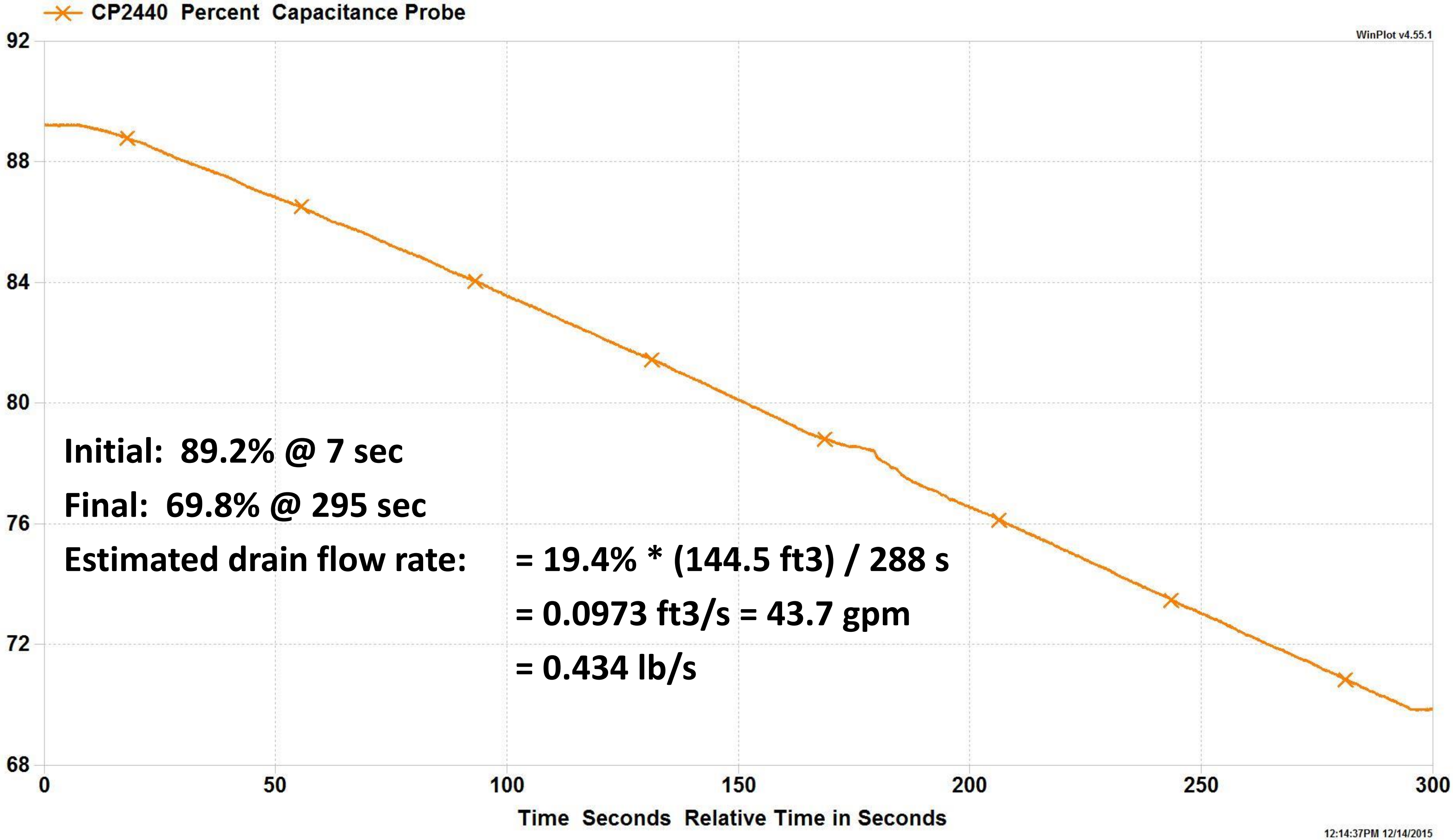


P6404 PSIA Gage Type Computed
WinPlot v4.55.1
40
36
32
28
24
20
16
12
-400
-300
-200
-100
0
100
200
300
400
Time Seconds Relative Time in Seconds
12:33:01PM 12/14/2015
Pre-Press
Drain
Significant overshoot during first pre-press cycle
Initial Ullage Pressure: 15.3 psia

Temperature



Tank Fill Level by Capacitance Probe



Initial: 89.2% @ 7 sec

Final: 69.8% @ 295 sec

Estimated drain flow rate: = 19.4% * (144.5 ft3) / 288 s

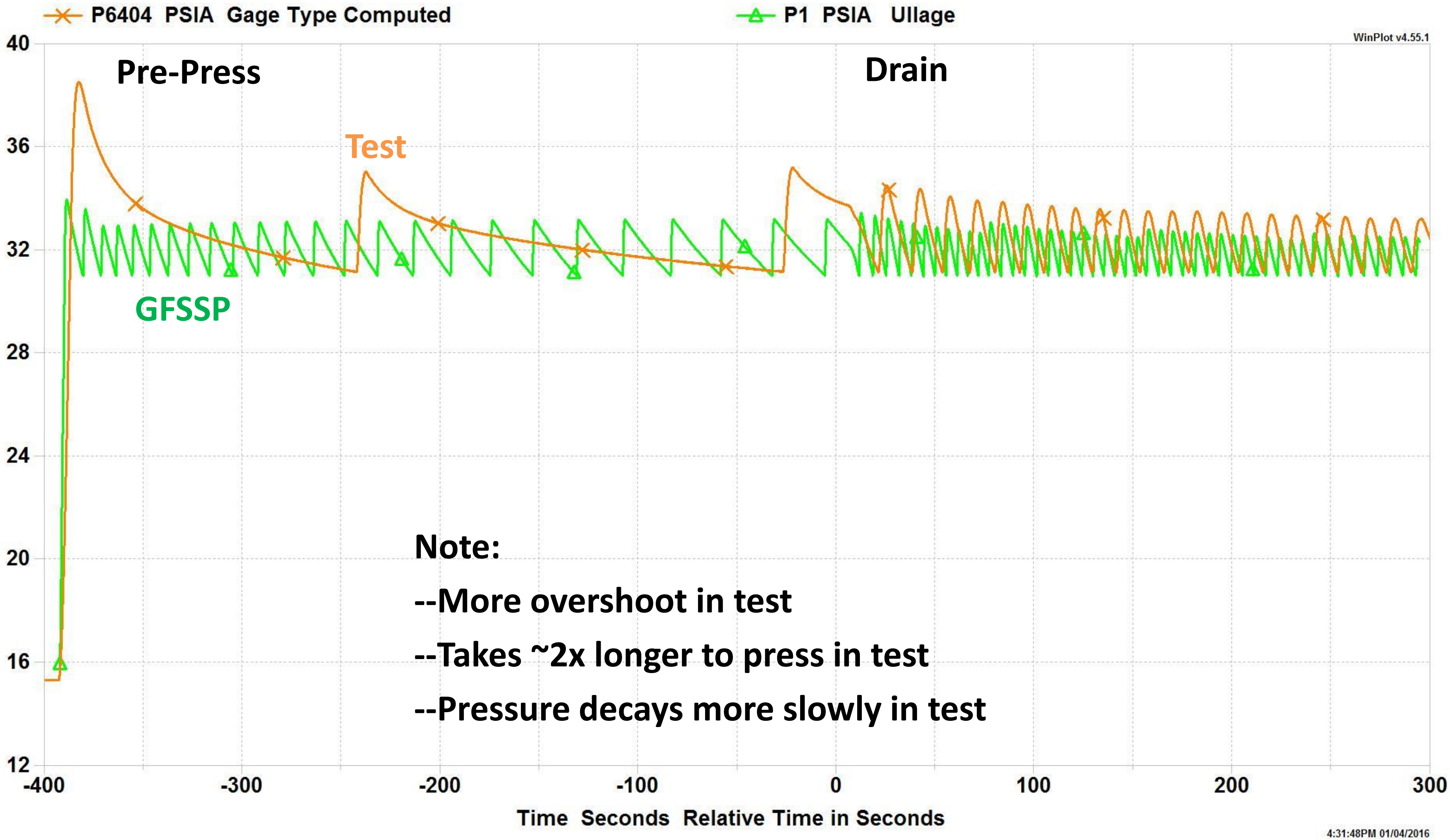
= 0.0973 ft3/s = 43.7 gpm

= 0.434 lb/s

Results of 1st Run

- **Ullage pressure rises more quickly in model.**
- **Ullage pressure overshoot is much less in model.**
- **Decay of ullage pressure is <u>much</u> faster in model.**
- **Therefore, many more pressure cycles in model.**
- **Difficult to compare GFSSP's temperature in the single ullage node to the multiple ullage temperature measurements, but model ullage temperature appears to be "in range".**
- **Model pressure upstream of orifice is ~10% higher than test measurement. Suggests model flow rate is ~10% higher. (Some uncertainty because orifice C_D is unknown. Assumed 0.84.)**
- **Model pressure downstream of orifice decays much more quickly than measured pressure. Suggests gas in downstream press lines takes its time reaching the tank.**

Ullage Pressure



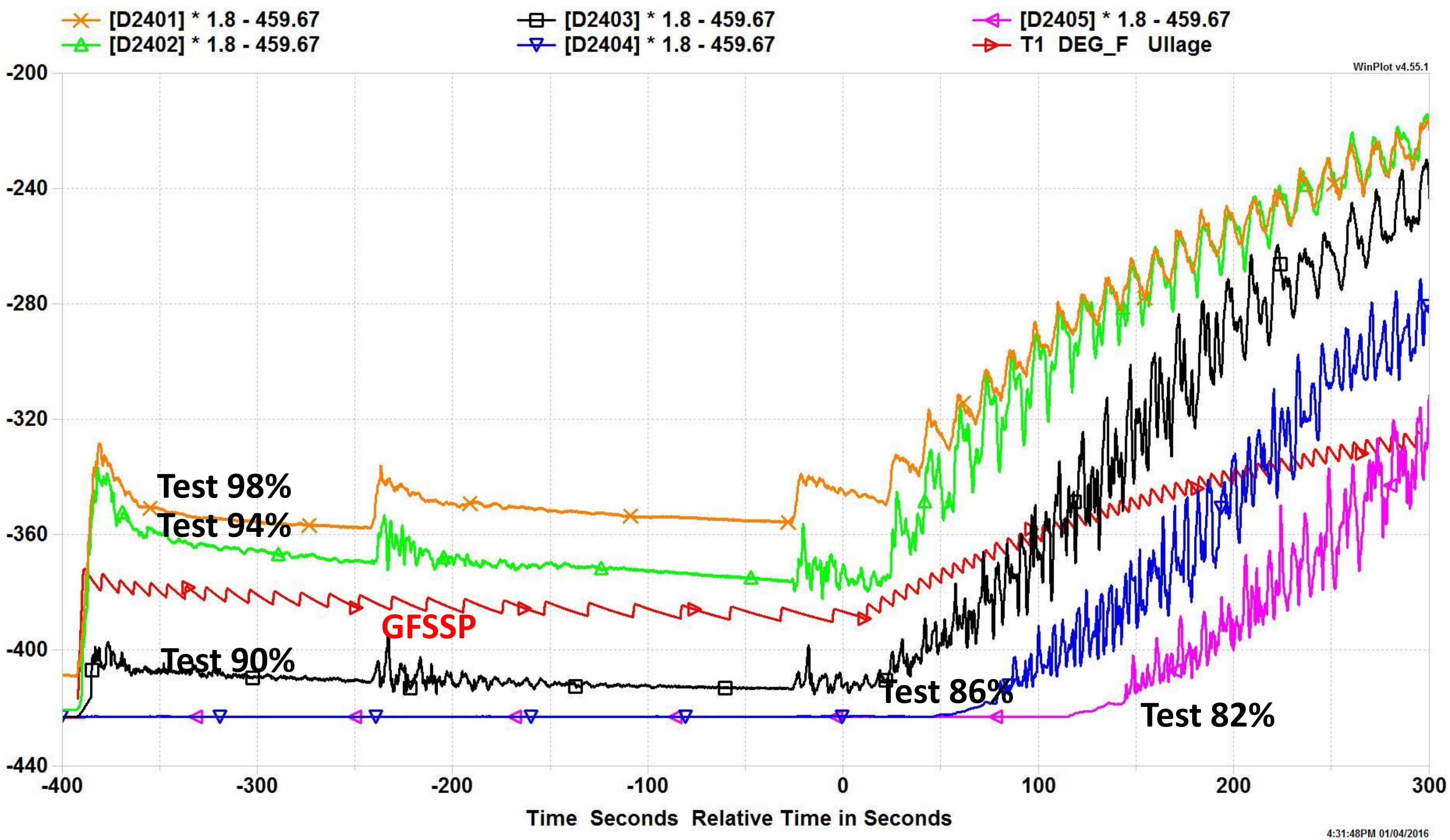
Note:

--More overshoot in test

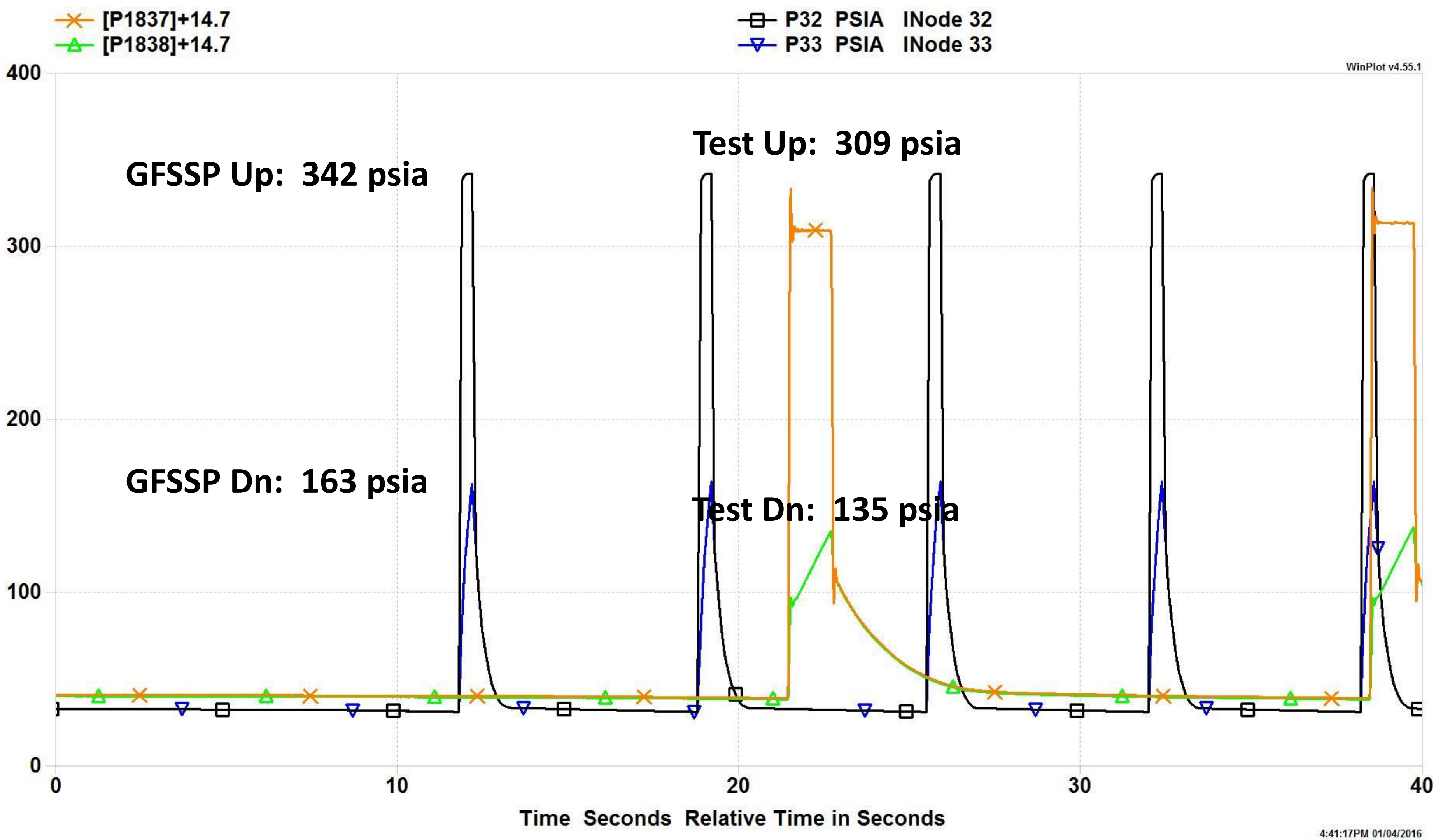
--Takes ~2x longer to press in test

--Pressure decays more slowly in test

Ullage Temperature



Pressure at Orifice



Note: Pressure decay is much slower in test

Run #2

- **A series of parametric runs were carried out to investigate the effect of various model inputs on ullage pressure rise and decay.**
- **Changes:**
  - **Control valve C_D reduced from 0.6 to 0.5.**
  - **Set heat transfer correction factor to 0.1.**
  - **Add 200 in^3 of extra volume to represent press line to aft diffuser.**
  - **Set temperature of pressurant to match measured diffuser temperature.**

Case	Init. P_{ull} (psia)	Init. Press Time (s)	Init. Decay Time (s)	Valve Cycles
Run #1	33.9	2.5	8.3	73
Run #2	32.8	13.5	75	32
Test Data	38.5	5.4	140	24

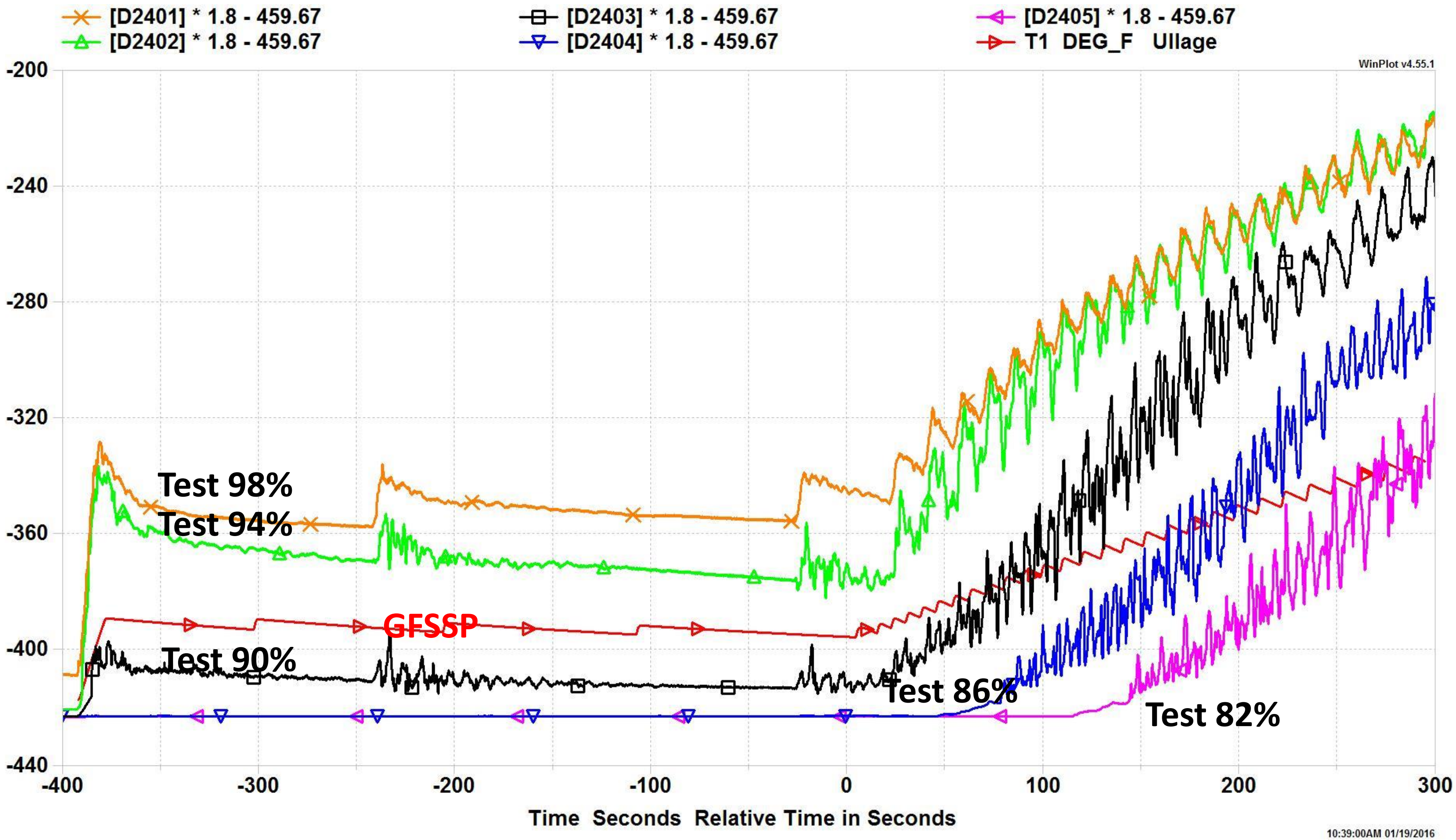
Ullage Pressure

Note:

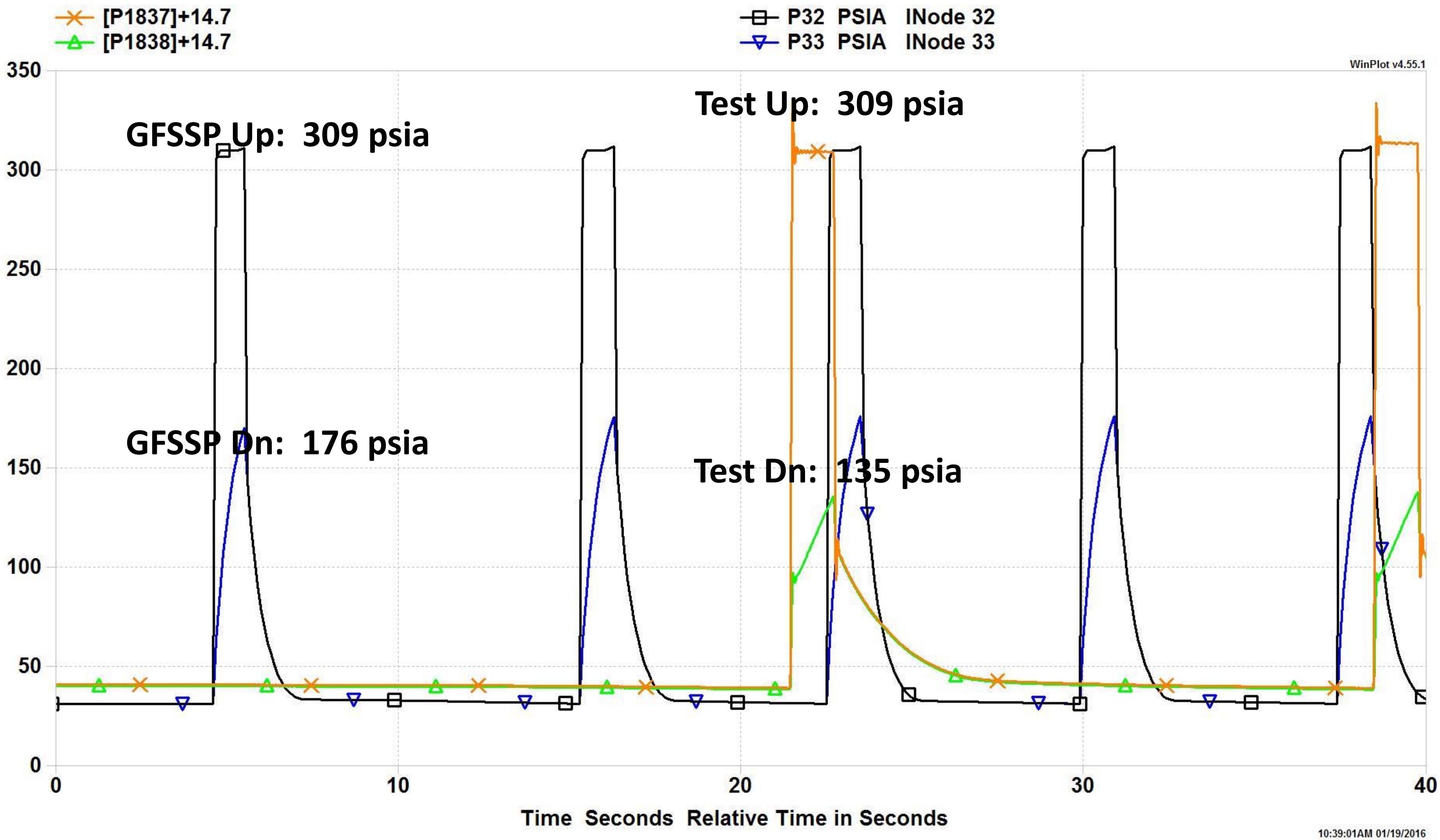
--More overshoot in test

--Pressure decay rate is now similar to test, but decay takes longer in test because of more overshoot.

Ullage Temperature



Pressure at Orifice



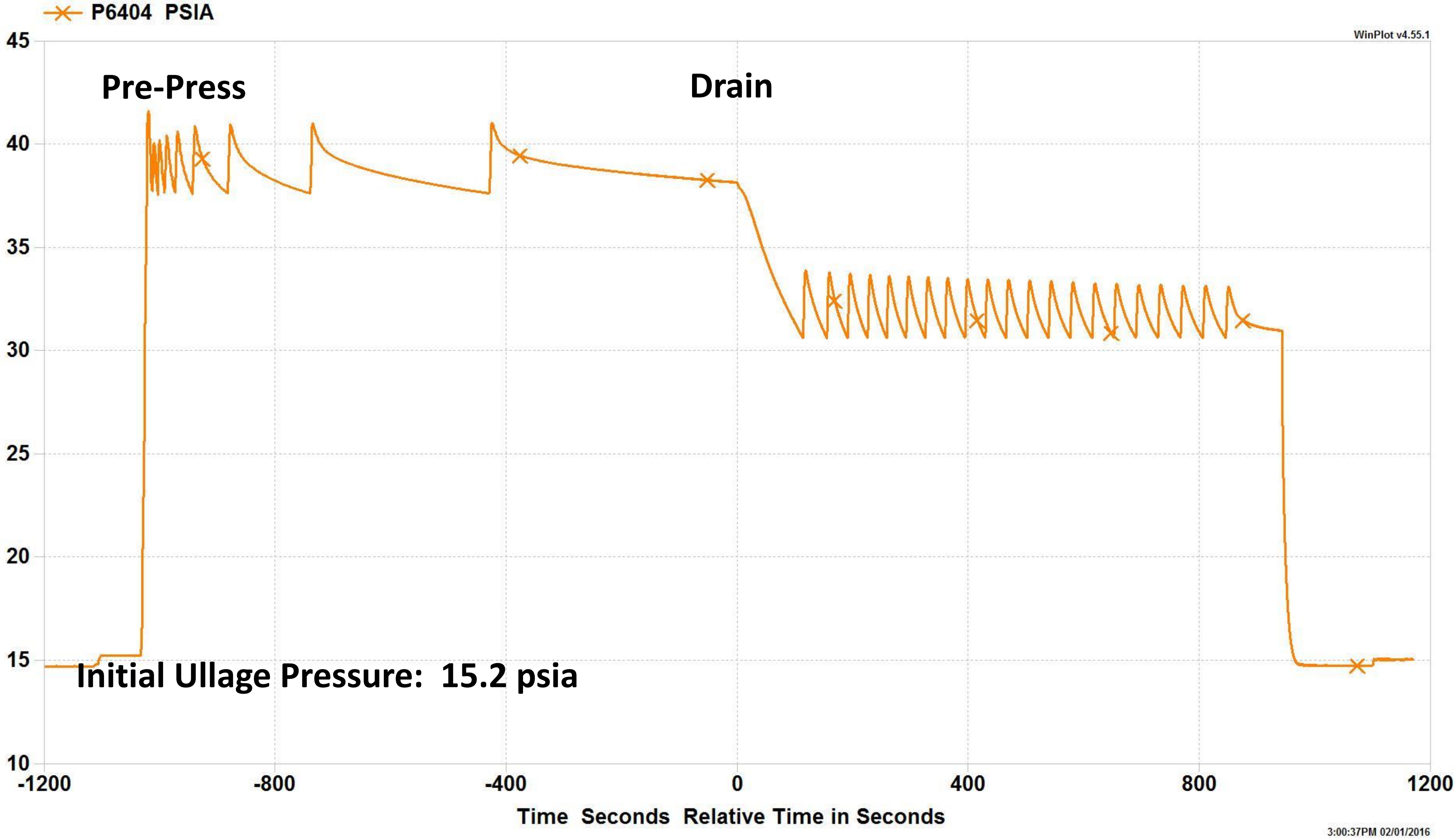
Note: Pressure decay is much slower in test

LN_2 Test Description

- LN2 propellant
- He pressurant
- Bang-bang valve set to maintain 37.5 – 38.5 psia range during pre-press, and 31 – 32 psia range during drain.
- Tank drains from 90.3% to 69.9%.
- Pre-press starts at ~T-1032 sec.
- Drain starts at ~T-0 sec.
- Drain stops at ~T+864 sec.

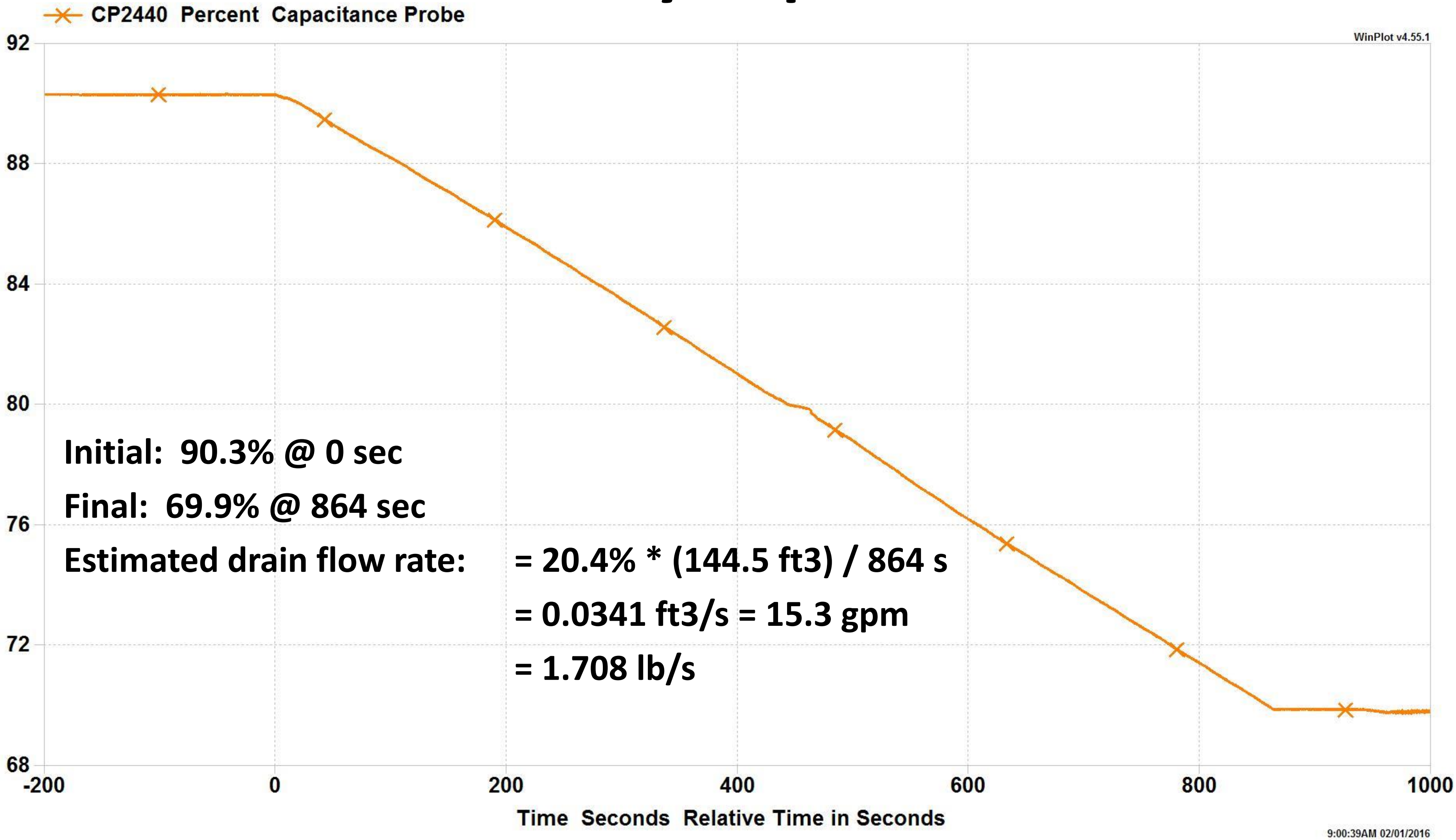
- Adjustments developed for LH2 model are retained in LN2 model:
  - Control valve C_D reduced from 0.6 to 0.5.
  - Set heat transfer correction factor to 0.1.
  - Add 200 in^3 of extra volume to represent press line to aft diffuser.
  - Set temperature of pressurant to match measured diffuser temperature.

Pressure



P6404 PSIA
WinPlot v4.55.1
Pre-Press
Drain
Initial Ullage Pressure: 15.2 psia
45
40
35
30
25
20
15
10
-1200
-800
-400
0
400
800
1200
Time Seconds Relative Time in Seconds
3:00:37PM 02/01/2016

Tank Fill Level by Capacitance Probe



Initial: 90.3% @ 0 sec

Final: 69.9% @ 864 sec

Estimated drain flow rate: = 20.4% * (144.5 ft3) / 864 s

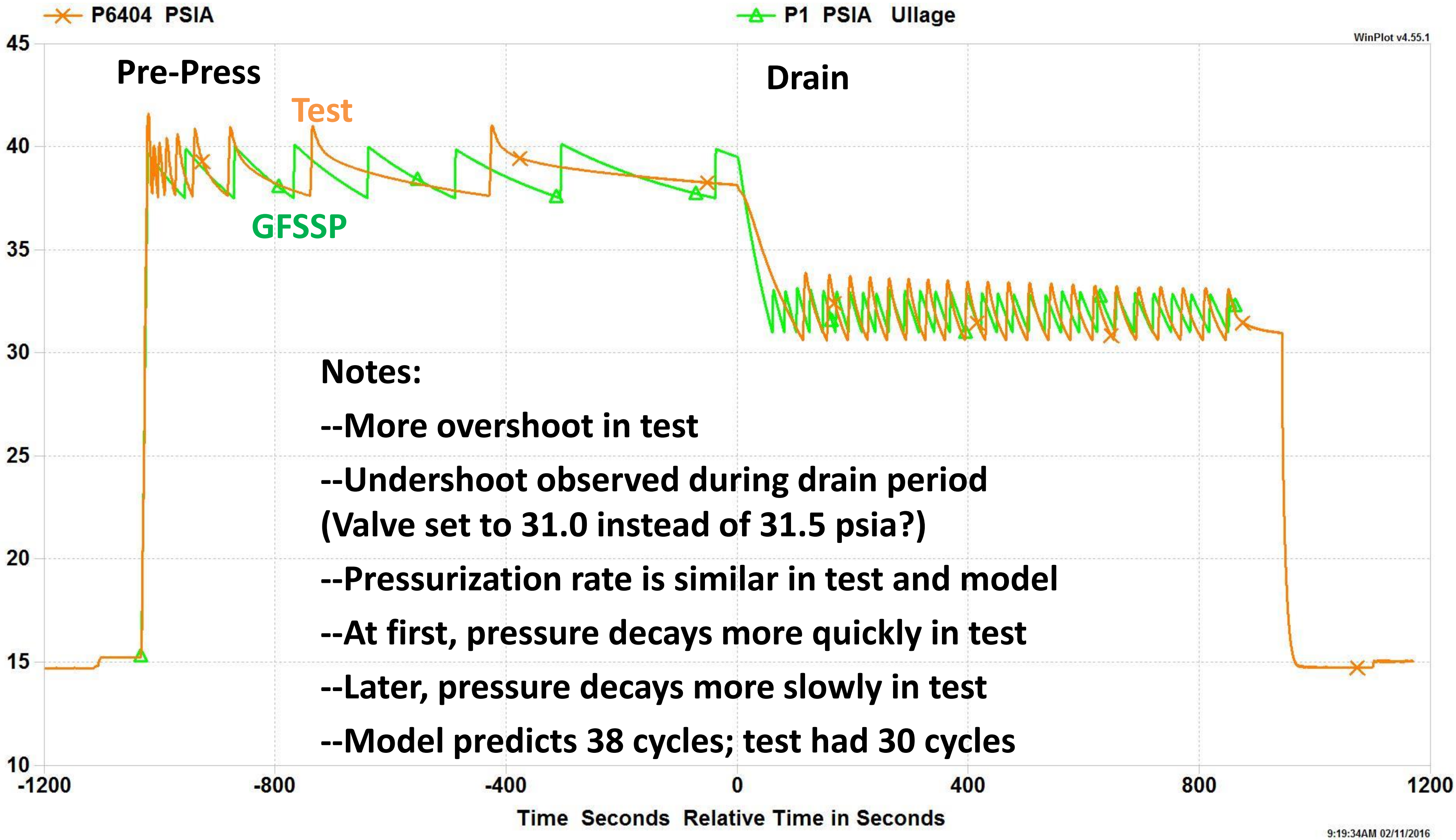
= 0.0341 ft3/s = 15.3 gpm

= 1.708 lb/s

Results of 1st Run

- **Rate of ullage pressure rise in model is similar to test.**
- **Ullage pressure overshoot is much less in model.**
- **Decay of initial ullage pressure (when tank isn't draining) is <u>much</u> slower in model.**
- **But after a few cycles, decay of ullage pressure is faster in model than in test.**
- **Difficult to compare GFSSP's temperature in the single ullage node to the multiple ullage temperature measurements, but model ullage temperature appears to be "in range".**
- **Model pressure downstream of orifice decays much more quickly than measured pressure. Suggests gas in downstream press lines takes its time reaching the tank.**

Ullage Pressure



Notes:

--More overshoot in test

--Undershoot observed during drain period
(Valve set to 31.0 instead of 31.5 psia?)

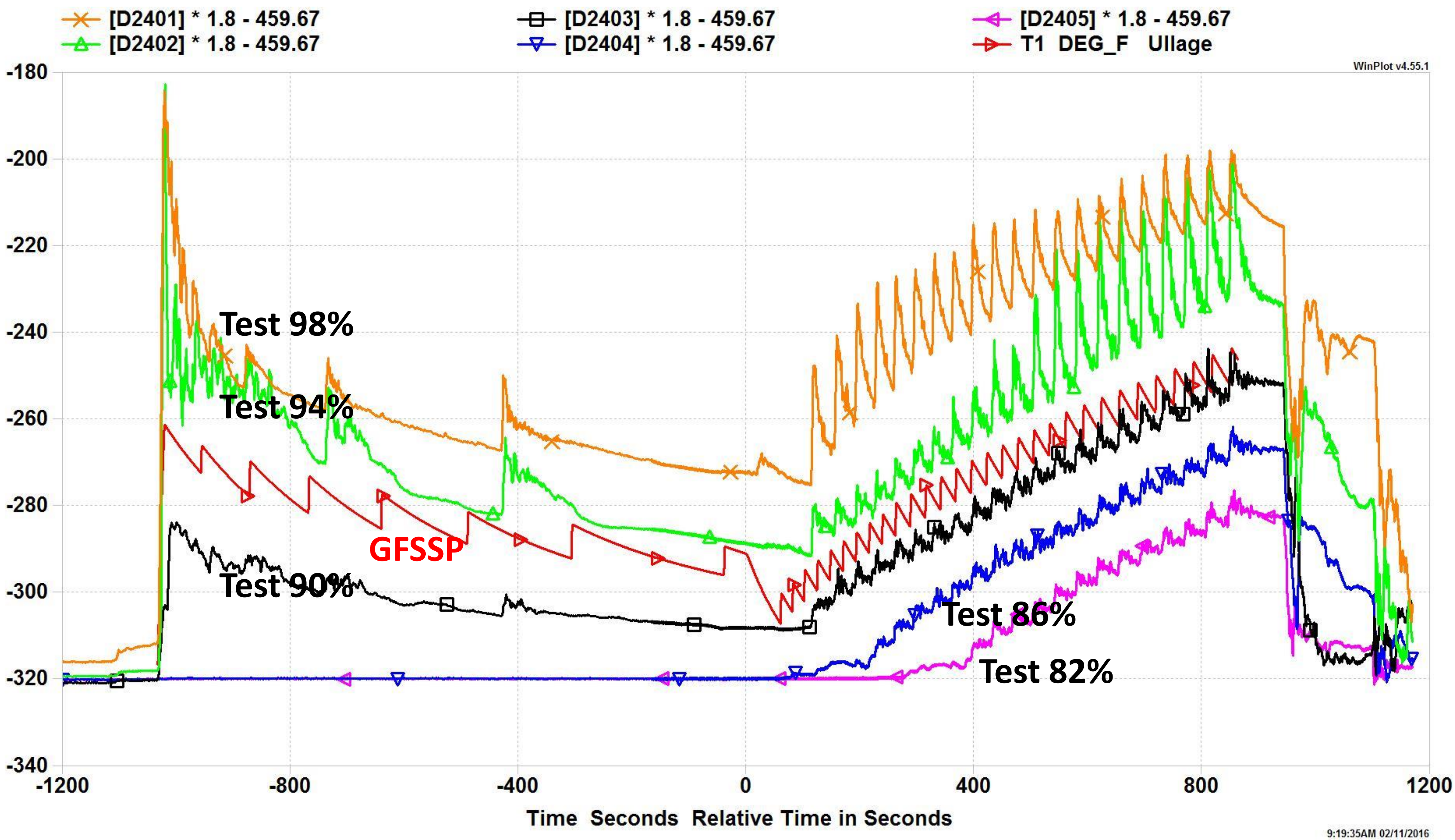
--Pressurization rate is similar in test and model

--At first, pressure decays more quickly in test

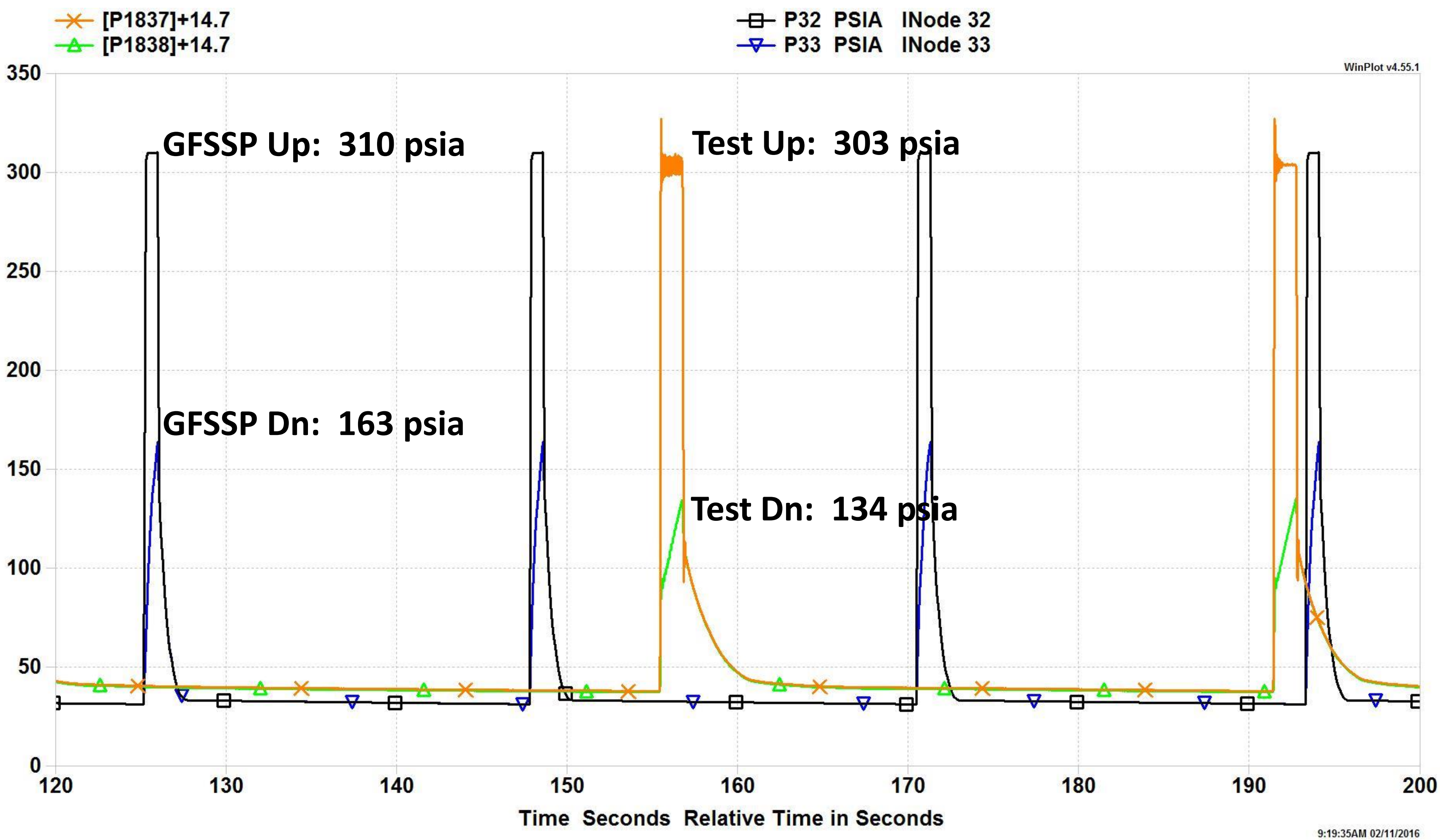
--Later, pressure decays more slowly in test

--Model predicts 38 cycles; test had 30 cycles

Ullage Temperature



Pressure at Orifice



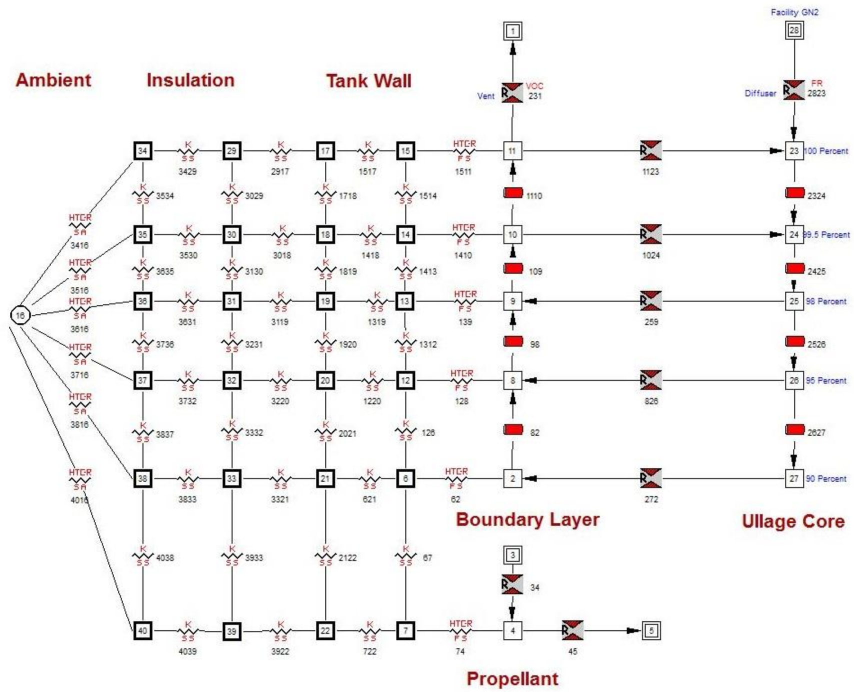
Note: Pressure decay is much slower in test

Discussion

- Heat transfer is the greatest uncertainty in pressurization modeling.
  - The natural convection correlations recommended by Ring (1964) significantly over-predicted the heat transfer for this tank and diffuser.
  - Past modeling of FASTRAC tests did not require this correction factor. Perhaps the large Stennis facility tank better approximates a flat plate.
  - The single-node ullage approach is an approximation which doesn’t capture temperature stratification in the ullage. Results may be better with a well-mixed ullage.
- Uncertainty in the total volume of the press line also appears to be significant.
  - Test data always shows more overshoot than predicted by model.
  - Test data shows facility line pressure decays much more gradually than predicted by model.
- There were no measurements of pressurant temperature just as it enters the tank. This would be desirable in future testing.
- Almost all of the pressure drop in the press system occurred in the valves and control orifice. Pipe roughness and minor losses from bends had little effect. The press system portion of the model could probably be greatly simplified.

Forward Work

- The project has continued with pressurization testing of a larger (4500 gal) tank, with a flight-like diffuser (spring 2016) and an injector (summer 2016).
- We are exploring multi-node ullage set-ups to approximate stratification and mixing:



- We will explore whether the single-node ullage heat transfer is better modeled when there is strong mixing induced by an injector.